UCRL-JRNL-208783

Radiocarbon-Based Ages and Growth Rates of Bamboo Corals from the Gulf of Alaska

E. B. Roark, T. P. Guilderson, S. Flood-Page, R. B. Dunbar, B. L. Ingram, S. J. Fallon, M. McCulloch

December 29, 2004

Geophysical Research Letters

Disclaimer

Radiocarbon-Based Ages and Growth Rates of Bamboo Corals from the Gulf of Alaska

E. Brendan Roark[1], Thomas P. Guilderson[2,3], Sarah Flood-Page[4], Robert B. Dunbar[5], B. Lynn Ingram[1,6], Stewart J. Fallon[2], and Malcolm McCulloch[7]

[1]Department of Geography, University of California, Berkeley, CA 94720-4740

510-642-2381; Fax 510-642-3370; E-mail ebroark@socrates.berkeley.edu

[2]Center for Accelerator Mass Spectrometry, LLNL, L-397 7000 East Av. Livermore CA 94551;

[3]Department of Ocean Sciences and Institute of Marine Sciences, University of California, Santa Cruz, Santa Cruz CA 95064

[4]Department of Biological Sciences University of California, Santa Cruz Santa Cruz, CA 95064

[5]Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115

[6]Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767

[7]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia

Index Terms: 6206 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4808 Oceanography: Biological and chemical: Chemical tracers; 4875 Oceanography: Biological and chemical: Trace elements; 1050 Geochemistry: Marine geochemistry.

Keywords: coral age validation, coral chemistry, Gulf of Alaska.

Submitted for publication in *Geophysical Research Letters.*

Deep-sea coral communities have long been recognized by fisherman as areas that support large populations of commercial fish. As a consequence, many deep-sea coral communities are threatened by bottom trawling. Successful management and conservation of this widespread deep-sea habitat requires knowledge of the age and growth rates of deep-sea corals. These organisms also contain important archives of intermediate and deep-water variability, and are thus of interest in the context of decadal to century-scale climate dynamics. Here, we present $\Delta^{14}C$ data that suggest that bamboo corals from the Gulf of Alaska are long-lived (75-126 years) and that they acquire skeletal carbon from two distinct sources. Independent verification of our growth rate estimates and coral ages is obtained by counting seasonal Sr/Ca cycles and probable lunar cycle growth bands.

1. Introduction

Deep-sea coral communities (DSCC) are attracting attention because of their near global distribution, the large depth range over which they occur, and the biodiversity they support. Many DSCC are important habitats for commercial fish species [e.g. *Witherell et al.*, 2000] as well as for the precious coral trade [e.g. *Grigg*, 1976; *Grigg*, 1993]. Most deep sea corals have large yet fragile skeletons and the recent expansion of commercial bottom-trawl fisheries constitutes a significant threat in some areas [*Hall-Spencer et al.*, 2002; *Krieger*, 2000].

There is increasing interest in the development of biogeochemical proxy records of climatic and environmental changes contained in the skeletons of deep-sea corals. Few archives have the potential to reconstruct time series of oceanographic tracers of intermediate and deep-water masses at annual to decadal scales over centuries to millennia. The development of conservation strategies and paleoclimate proxy reconstructions both require the precise determination of coral ages and growth rates. Age and growth rate information is not yet available for most deep-sea coral species. Methods for determining age and growth rates include tagging [*Grigg*, 1976; *Stone and Wing*, 2000], limited growth band counting [*Grigg*, 1976; *Wilson et al.*, 2002], and radiometric techniques (U/Th, ^{210}Pb ^{14}C) [*Adkins et al.*, 2004; *Andrews et al.*, 2002; *Cheng et al.*, 2000; *Druffel et al.*, 1995; *Druffel et al.*, 1990; *Griffin and Druffel*, 1989; *Risk et al.*, 2002].

Here, we present radiocarbon-based growth rates and age estimates for three bamboo coral specimens collected live at ~700 meters using the DSRV Alvin in June 2002 at Warwick Seamount, Gulf of Alaska (48° 3'N, 132° 44'W). Samples were identified as members of the family Isididae *(Keratoisis*, *Isidella*, or *Acanella spp.)*. More precise identification is not possible as samples exhibit multiple morphological characteristics of genera previously seen in only one given species. Bamboo corals (family Isididae, order Alycyonacea) are gorgonian octocorals that have a two-component skeleton composed of calcite internodes several centimeters long interspersed with proteinaceous gorgonin nodes 4-8 mm thick. Samples typically grow in a candelabra-like shape to heights greater than 2 m.

2. Samples

Three specimens with different basal diameters were used in this study (Table 1). The bottom-most and presumably oldest gorgonin node along with a ~4mm thick carbonate section from just below the gorgonin node were cut from each sample as disks. These cross-sectional wafers were circular from samples 3808-#3 and 3808-#4 and oblong from sample 3808-#5. Concentric banding visible within the wafers suggests coeval radial growth in adjacent gorgonin and carbonate sections; thus sampling along a radial transect extending outward from the center of a node or inter-node sample is presumed to yield skeletal material accreted over the life of the specimen.

3. Methods

Three different methods were employed to estimate sample age. The first method consisted of measuring the ^{14}C activity along transects. Gorgonin and carbonate disks were milled along a radial transect from the center of the sample to the outer edge. Cuts were 1 mm wide by 2 mm deep at 1 mm intervals and ~1.5 mg and ~2.0 mg of material was obtained from the gorgonin and carbonate sections respectively. CO_2 aliquots evolved from calcite and decalcified gorgonin samples were reduced to graphite for AMS measurement of $\Delta^{14}C$. The second method utilized counts of cycles in Sr/Ca ratios in coral calcite as measured by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). These analyses were conducted across a radial transect from the bottom carbonate section of sample 3808-#3 following the technique of Fallon *et al*., [2003]. The final method was counting of visible growth bands using a 30 µm thick thin-section from the sample 3808-#3 wafer that was also used for Sr/Ca analysis. Digital photographs of 100 µm wide fields-of view of the thin section were taken using a Nikon Eclipse E600 POC microscope in transmitted light mode and a Polaroid Digital Microscope Camera. Couplets composed of light and dark rings were counted within the outer 6.5mm of the wafer (65 fields-of-view) where growth bands were easily distinguished. In 13 of the 100µm fields-of-view, growth bands were not clearly discernable, in which case the average number of growth rings in the adjacent fields-of-view were used to estimate the total number of bands in this section.

4. Radiocarbon Results

Gorgonin $\Delta^{14}C$ values of bamboo coral 3808-#3 range from –100‰ at the center to 24‰ at the outer margin with a maximum value of 100‰ 2.5mm from the outer edge (Fig. 1). Calcite $\Delta^{14}C$ values from this specimen range from –188‰ at the center to –162‰ at the outer edge. Elevated ^{14}C values above regional seawater reservoir ages are the result of bomb-^{14}C introduced during atmospheric nuclear testing in the late 1950s and 1960s. Gorgonin $\Delta^{14}C$ values above –100‰ reflect the bomb-^{14}C transient. Carbonate $\Delta^{14}C$ shows a 26‰ increase reflecting the penetration of bomb-^{14}C from surface waters into intermediate depths of the sub-polar North Pacific.

Comparison of $\Delta^{14}C$ of the outermost samples of calcite and gorgonin and of live polyp tissues from sample 3808-#3 shows that the gorgonin (24‰) and tissue samples (20‰) are similar to surface water $\Delta^{14}C$ values (18‰) (Fig. 2). In contrast, the outer calcite value (-162‰) is equivalent to modern seawater $\Delta^{14}C$ at 700m (-170‰) sampled at the same time from this location. Coral calcite $\Delta^{14}C$ records dissolved inorganic carbon (DIC) $\Delta^{14}C$ at ~700m whereas gorgonin and tissues have $\Delta^{14}C$ values reflective of surface seawater $\Delta^{14}C$. This suggests that recently exported particulate organic carbon (POC) is the source of carbon for both living tissues and the gorgonin nodes. Isotopic and elemental data from gorgonin thus have the potential to record surface ocean biogeochemistry while similar measurements from carbonate section should yield a time-series of environmental changes at depth [*Heikoop et al.*, 2002].

For reliable development of paleoenvironmental time series using radiocarbon and other tracers, independent ages and growth rates must be determined. The bomb $\Delta^{14}C$ values in the gorgonin section are virtually identical to a surface water $\Delta^{14}C$ time series reconstructed by measuring $\Delta^{14}C$ in salmon scales from the Gulf of Alaska [*Brown et al.*, 1998] and thus it is possible to assign ages to certain $\Delta^{14}C$ values. For sample 3808-#3 we assign an age of A.D. 1957 to the initial increase in $\Delta^{14}C$ values at 5.5 mm from the outer edge (Table 1) and an age of A.D. 1970 to the peak $\Delta^{14}C$ value ($\Delta^{14}C$ = 99‰). The outermost edge of the specimen reflects the collection date in A.D. 2002. The estimated linear growth rate between 1957 and 2002 is therefore 120μm year^{-1}, which if applied to the full radial distance of 9 mm, suggests that the sample is ~75 years old (Table 1). An error of ±3 years in the assignment of 1957 to the initial increase in $\Delta^{14}C$ is used to calculate the error in growth rate and age (Table 1).

$\Delta^{14}C$ profiles from the other two corals are nearly identical to that observed in sample 3808-#3. Linear growth rates and age estimates were calculated in a similar fashion (Fig. 3, Table 1). The larger sample is older but also exhibits higher growth rates (Table 1). $\Delta^{14}C$ profiles from these three specimens shows that gorgonin from bamboo corals can be used to calculate growth rates and ages with an error of less than 15%. Our results imply that larger individuals may be growing faster than smaller ones, presumably due to the larger surface area presented into the currents delivering the organic particles on which the polyps are feeding, thus providing more resources for growth. This is consistent with culture feeding experiments using solitary stony corals. It also suggests that the growth rate is not uniform over the life of the sample and that the age estimates based on the faster growth over the outer portions are minimum ages.

5. Independent Age Verification

Independent verification of the gorgonin $\Delta^{14}C$ ages and a method of developing high-resolution growth rates in the carbonate skeleton was sought using growth bands. A thin section from the base of sample 3808-#3 reveals alternating light and dark growth rings (Fig. 4). Over the outer 6.5mm of the sample, a total of 517 growth rings were counted resulting in an average of 8 growth ring per 100 µm interval. Annual growth bands are thought to form in some deep sea corals and have been counted to estimate age *[Grigg, 1976; Wilson et al., 2002]*. Our $\Delta^{14}C$-derived ages imply that these features are not annual growth rings, but more likely form at the timescale of the monthly lunar cycle (e.g., we see about 12 growth bands over a distance of 120 µm, the average growth per year based on $\Delta^{14}C$). The growth rings are not consistent with annual periodicity and an alternative method must be considered.

LA-ICP-MS Sr/Ca ratios along a radial transect of a calcite wafer from sample 3808-#3 range from 5.1 to 5.9 mmol/mol and show 84 clear cycles (Fig. 5). An age of 84 years is broadly consistent with our gorgonin $\Delta^{14}C$-derived age model, implying that these Sr/Ca cycles are annual. The ^{14}C derived growth rate and age was calculated from the outer portion and is thus a maximum growth rate and minimum age calculation. Our observation between smaller samples and slower growth rates supports this conclusion. We observe good agreement between the calcite Sr/Ca cycle counting and $\Delta^{14}C$ in the gorgonin age-estimation techniques. If the lunar periodicity of the growth rings is accepted then this method provides an additional chronological control.

Next we consider the origins of apparent lunar monthly growth rings and annual Sr/Ca cyclicity in deep-sea organisms from an environment that is characterized by near-constant physical conditions. *In-situ* temperature at 700m is ~3.4°C and varies seasonally by ±0.2 °C. *In-situ* salinity and oxygen levels are 34.26 psu (±0.02) and 0.66 ml/l (±0.13) respectively. We suggest that the sub-annual to annual variance in growth features and Sr/Ca ratios reflect changes in food supply and hence coral growth rate. In a specimen of the deep sea coral *Corallium rubrum*, Sr/Ca ratios vary with skeletal density such that dark (light) bands are indicative of slow (fast) growth suggesting that Sr/Ca ratios can be used as an additional proxy for growth rate [*Weinbauer et al.*, 2000]. ^{14}C enrichment in gorgonin fractions show that the Gulf of Alaska bamboo corals are feeding on recently exported POC. In addition, zooplankton biomass is known to vary with lunar brightness in many parts of the ocean, with biomass at it's highest during the second lunar quarter and lowest after the full moon [*Hernandez-Leon et al.*, 2002]. A lunar-modulated change in zooplankton biomass may account for large changes in particulate flux, as observed in sediment traps [*Fischer et al.*, 1996]. Lunar and seasonal cycles [*Wong et al.*, 1999] in zooplankton biomass, and the resulting variability in POC export from surface to deep water likely affect food availability and therefore the growth rate of bamboo corals.

6. Discussion

The ages of these Gulf of Alaska bamboo corals are younger and the growth rates faster when compared to age-estimates and growth rates of other similarly-sized bamboo corals [*Thresher et al.*, 2004; *Tracey et al.*, 2003]. Carbonate ^{210}Pb and U-series measurements obtained from two *Keratoisis spp*. samples from Tasmania yield growth rates of 50µm/year and ages of 360 to 400 years with relatively large decadal uncertainties [*Thresher et al.*, 2004]. Concurrent ^{14}C estimates of 80-130 years for the samples conflict with these estimates. Due to the uncertainties involving ^{14}C production rates and carbon cycle transformations, the radiocarbon method is not useful in many cases for dating of materials that formed between the 1700s and 1950 [*Stuiver et al.*, 1998]. A 300-400 year ^{14}C calendar-age-estimate is consistent for these *Keratoisis*. These two sub-sets (Tasmania, Gulf of Alaska) have different growth rates likely governed by different POC export rates.

Our results show that radiocarbon based growth rates and ages within the gorgonin section of bamboo corals are possible and accurate to within a few years. Further more these ages and growth rates can be reproduced by an independent method (annual Sr/Ca cycles) in the carbonate section. As a consequence ages and growth rates of the both carbonate and gorgonin sections of these bamboo corals can be determined with sufficient resolution that we can develop proxy time series of surface and intermediate water conditions extending back at least 100 years within a single specimen. These results also show that bamboo corals are long lived, a consideration in their conservation and fisheries' management.

Acknowledgements:

This research was funded by the NOAA Office of Ocean Exploration (NA16RP2637). We thank the captain and crew of the R/V Atlantis, the DSRV Alvin pilots and engineers, and the GoASEx science party. DIC extraction courtesy of P.D. Quay, Univ. of Washington. Radiocarbon analyses were performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory (contract W-7405-Eng-48). Data will be archived at WDC-A, Boulder CO.

REFERENCES

Adkins, J. F., G. M. Henderson, S.-L. Wang, S. O'Shea, and F. Mokadem (2004), Growth rates of the deep-sea scleractinia *Desmophyllum cristagalli* and *Enallopsammia rostrata*, *Earth Planet. Sci. Lett.*, 227, 481-490.

Andrews, A. H., E. E. Cordes, M. M. Mahoney, K. Munk, K. H. Coale, G. M. Cailliet, and J. Heifetz (2002), Age, growth and radiometric age validation of a deep-sea. habitat-forming gorgonian (*Primnoa rededaeformis*) from the Gulf of Alaska, *Hydrobiologia*, 471, 101-110.

Brown, T. A., P. P. Quay, R. C. Francis, and D. Holmgren (1998), Radiocarbon time histories for subpolar North Pacific surface waters spanning the last 50 years, paper presented at AGU Spring Meeting, Boston MA.

Cheng, H., J. Adkins, R. L. Edwards, and E. A. Boyle (2000), U-Th dating of deep-sea corals, *Geochim. Cosmochim. Acta*, 64, 2401-2416.

Druffel, E. R. M., S. Griffin, A. Witter, E. Nelson, J. Southon, M. Kashgarian, and J. Vogel (1995), *Gerardia*: Bristlecone pine of the deep-sea?, *Geochim. Cosmochim. Acta*, 59, 5031-5036.

Druffel, E. R. M., L. L. King, R. A. Belastock, and K. O. Buesseler (1990), Growth rate of a deep-sea coral using Pb-210 and other isotopes, *Geochim. Cosmochim. Acta*, 54, 1493-1500.

Fallon, S. J., M. T. McCulloch, and C. Alibert (2003), Examining water temperature proxies in *Porites* corals from the Great Barrier Reef: a cross-shelf comparison, *Coral Reefs*, 22, 389-404.

Fischer, G., S. Neuer, G. Wefer, and G. Krause (1996), Short-term sediment pulses recorded with a flourescence sensor and sediment traps at 900-m depth in the Canary Basin, *Limnol. Oceanogr.*, 41, 1354-1359.

Griffin, S., and E. R. M. Druffel (1989), Sources of carbon to deep-sea corals, *Radiocarbon*, 55, 533-542.

Grigg, R. W. (1976), Fishery management of precious and stony corals in Hawaii, *Rep. UNIHI-SEAGRANT-TR-77-03*, 48 pp., University of Hawaii Sea Grant Program, Honolulu, 1976.

Grigg, R. W. (1993), Precious coral fisheries of Hawaii and the U.S. Pacific Islands, *Mar. Fish. Rev.*, 55, 50-60.

Hall-Spencer, J., V. Allain, and J. H. Fossa (2002), Trawling damage to Northeast Atlantic ancient coral reefs, *Proc. R. Soc. Lond., Ser. B: Biol. Sci.*, 269, 507-511.

Heikoop, J. M., D. D. Hickmott, M. J. Risk, C. K. Shearer, and V. Atudorei (2002), Potential climate signal from the deep-sea gorgonian coral Primnoa resedaeformis, *Hydrobiologia*, 471, 117-124.

Hernandez-Leon, S., C. Almeida, L. Yebra, and J. Aristegui (2002), Lunar cycle of zooplankton biomass in subtropical water: biogeochemical implications, *J. Plankton Res.*, 24, 935-939.

Krieger, K. J. (2000), Coral (*Primnoa*) impacted by fishing gear in the Gulf of Alaska, paper presented at First International Symposium on Deep-Sea Corals, Halifax, Nova Scotia.

Risk, M. J., J. M. Heikoop, M. G. Snow, and R. Beukens (2002), Lifespans and growth patterns of two deep-sea corals: *Primnoa resedaeformis* and *Desmophyllum cristagalli*, *Hydrobiologia*, 471, 125-131.

Stone, R., and B. Wing (2000), Growth and recruitement of an Alaskan shallow-water Gorgonian, paper presented at First International Symposium on Deep-Sea Corals, Halifax, Nova Scotia.

Stuiver, M., P. J. Reimer, and T. F. Braziunas (1998), High-precision radiocarbon age calibration for terrestrial and marine samples (AD 1950-9700), *Radiocarbon*, 40, 1127-1151.

Thresher, R., S. R. Rintoul, J. A. Koslow, C. Weidman, J. F. Adkins, and C. Proctor (2004), Oceanic evidence of climate change in southern Australia over the last three centuries, *Geophys. Res. Lett.*, 31, L07212, doi:07210.01029/02003GL018869.

Tracey, D., H. Neil, D. Gordon, and S. O'Shea (2003), Chronicles of the deep: ageing deep-sea corals on New Zealand waters, *Water and Atmosphere*, 11, 22-24.

Weinbauer, M. G., F. Brandstatter, and B. Velimirov (2000), On the potential use of magnesium and strontium concentrations as ecologocal indicators in the calcite skeleton of the red coral (*Corallium rubrum*), *Mar. Biol.*, 137, 801-809.

Wilson, M. T., A. H. Andrews, A. L. Brown, and E. E. Cordes (2002), Axial rod growth and age estimation of the sea pen, *Halipteris willemoesi* Kolliker, *Hydrobiologia*, 471, 133-142.

Witherell, D., P. Clarence, and D. Fluharty (2000), An ecosystem-based approach for Alaska groundfish fisheries, *ICES J. Mar. Sci.*, 57, 771-777.

Wong, C. S., F. A. Whitney, D. W. Crawford, K. Iseki, R. J. Matear, W. K. Johnson, J. S. Page, and D. Timothy (1999), Seasonal and interannual variability in particle fluxes of carbon, nitrogen, and silicon from time series of sediment traps at Ocean Station P, 1982-1993:relationship to changes in subarctic primary productivity, *Deep-Sea Research II*, 46, 2735-2760.

FIGURES

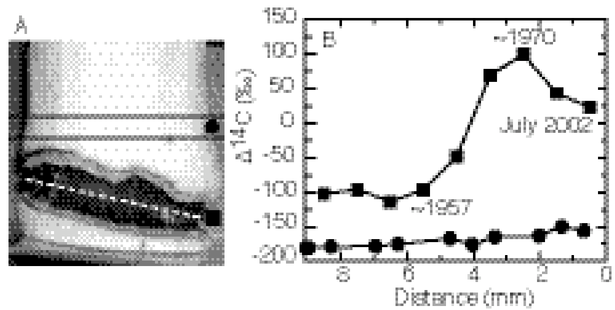

Figure 1. (a) Bamboo DSC ALV-3808#3 with lines showing disks cut from gorgonin (dashed) and carbonate (solid) sections. (b) $\Delta^{14}C$ measurements from radial transects of the carbonate disk (closed circles) and gorgonin disk (closed squares). Labeled dates are assigned to certain $\Delta^{14}C$ values by comparison of the bomb curve in the gorgonin section to a surface water $\Delta^{14}C$ time series and collection date.

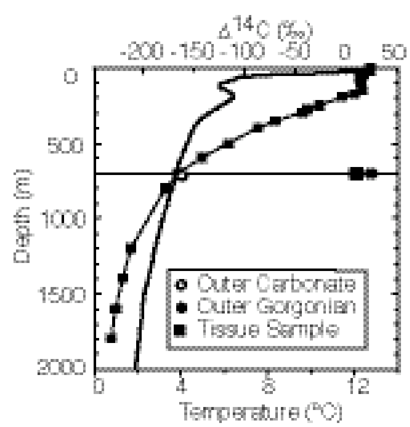

Figure 2. Temperature (solid line) and $\Delta^{14}C$ water (connected closed squares) profiles down to 1800 m. for Warwick Seamount. The $\Delta^{14}C$ values of the outer edge of the gorgonin section (closed circle), the outer edge of the carbonate section (open circle), and the tissue (closed square) of bamboo sample ALV-3808#3 are plotted at the depth

(720m.) from which the sample was collected. The gorgonin and tissue $\Delta^{14}C$ values are clearly equal to surface water $\Delta^{14}C$ values while the carbonate $\Delta^{14}C$ values are equal to the $\Delta^{14}C$ values of water at 700m.

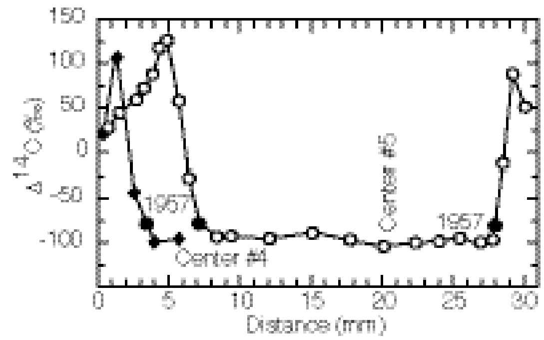

Figure 3. $\Delta^{14}C$ measurements from the gorgonin sections of two different bamboo corals collect at ~700m on Warwick Seamount. Labeled dates (closed circle) are assigned as in figure 1. Sample ALV-3808#4 (closed diamond) is a radial transect from the outer edge to the center. Sample ALV-3808#5 (open circles) is a transect across the entire sample because the growth was not symmetric about the center.

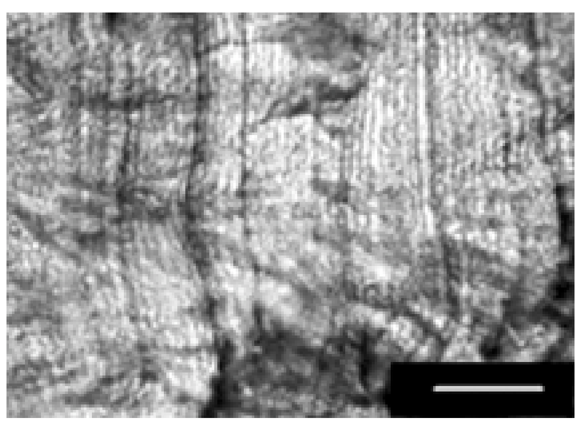

Figure 4. Photomicrograph (10x) from a thin section of a carbonate disk from a bamboo DSC, sample ALV-3808#3 showing growth banding. The finest-scale bands are

separated by about 10 µm. Several different hierarchical relationships between bands are present. The finer bands may well represent growth variability at the lunar monthly time-scales. The scale bar = 100µm.

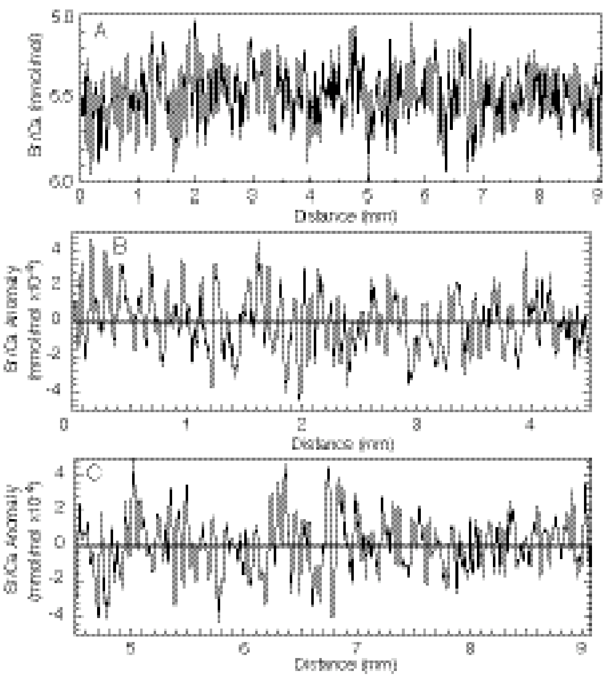

Figure 5. (a) LA-ICP-MS Sr/Ca ratios (3 pt smoothing) across entire radius of sample 3808-#3. Sr/Ca anomaly calculated by subtraction of the mean value plotted verses distance 0-4.5 mm (b) and 4.5-9 mm (c). 84 annual cycles were determined by a clear negative anomaly followed by a clear positive anomaly.

TABLES

Table 1: Growth rates and ages bamboo corals.

Sample ID	Depth (m)	Radial Length (mm)	1957-2002 growth rate (mm/year)[a]	Estimated Age (years)
ALV3808#3	720	9.0	0.12±0.01	75±5
ALV3808#4	704	5.7	0.09±0.01	64±4
ALV3808#5-long	634	20.1	0.16±0.01	126±8
ALV3808#5-short	634	10.m	0.05±0.01	208±42

[a]We make a functional definition of pre-bomb values as those taken prior to 1957 accepting that there may be local/ regional differences leading to an assumed uncertainty of 3 years.

Radiocarbon based ages and growth rates of bamboo corals from the Gulf of Alaska
Roark et al., Figures

Figure 1

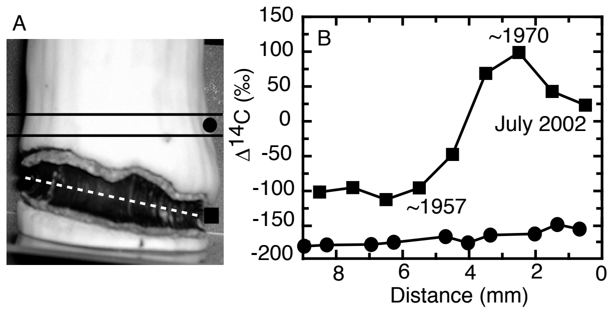

Figure 2

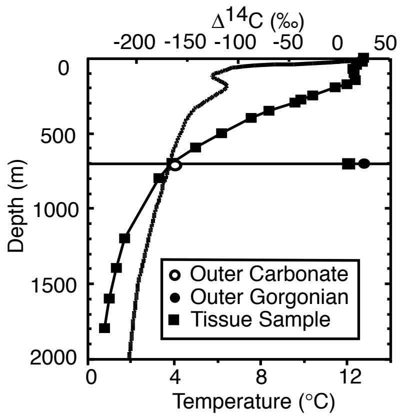

Figure 3

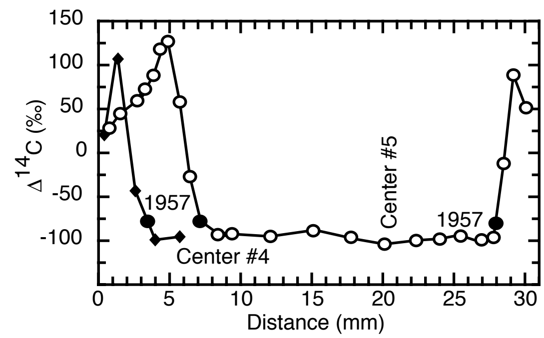

Figure 5

Figure 4